REAL-TIME FEEDBACK METHODS FOR GAIT REHABILITATION THROUGH A MOBILE PLATFORM

by

Matthew Grant Schmidt

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STATEMENT OF THESIS APPROVAL

The thesis of **Matthew Grant Schmidt**

has been approved by the following supervisory committee members:

Stacy Morris Bamberg	, Chair	**10 August 2012** Date Approved
Donald Bloswick	, Member	**10 August 2012** Date Approved
K. Bo Foreman	, Member	**10 August 2012** Date Approved

and by **Timothy Ameel** , Chair of

the Department of **Mechanical Engineering**

and by Donna M. White, Interim Dean of The Graduate School.

ABSTRACT

Computing and data acquisition have become an integral part of everyday life. From reading emails on a cell phone, to kids playing with motion sensing game consoles, we are surrounded with sensors and mobile devices. As the availability of powerful mobile computing devices expands, the road is paved for applications in previously limited environments. Rehabilitative devices are emerging that embrace these mobile advances. Research has explored the use of smartphones in rehabilitation as a means to process data and provide feedback in conjunction with established rehabilitative methods. Smartphones, combined with sensor embedded insoles, provide a powerful tool for the clinician in gathering data and may act as a standalone training technique.

This thesis presents continuing research of a sensor integrated insole system that provides real-time feedback through a mobile platform, the Adaptive Real-Time Instrumentation System for Tread Imbalance Correction (ARTISTIC). The system interfaces a wireless instrumented insole with an Android smartphone application to receive gait data and provide sensory feedback to modify gait patterns. Revisions to the system hardware, software, and feedback modes brought about the introduction of the ARTISTIC 2.0.

The number of sensors in the insole was increased from two to 10. The microprocessor and a vibrotactile motor were embedded in the insole and the communications box was reduced in size and weight by more than 50%. Stance time measurements were validated against force plate equipment and found to be within 13.5 ± 3.3% error of force plate time measurements. Human subjects were tested using each of the feedback modes to alter gait symmetry. Results from the testing showed that more than one mode of feedback caused a statistically significant change in gait symmetry ratios ($p < 0.05$). Preference of feedback modes varied among subjects, with the majority agreeing that several feedback modes made a difference in their gait. Further improvements will prepare the ARTISTIC 2.0 for testing in a home environment for extended periods of time and improve data capture techniques, such as including a database in the smartphone application.

To my wife, my family, and all the mentors who helped me discover my potential.

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CHAPTER 1

INTRODUCTION

Walking is an essential motor function in humans. It is the primary mode of personal transport. Gait is the manner in which walking is accomplished. It describes the specificities and nuances of individual walking patterns. There are various spatial and temporal methods to measure gait. Common measurements include stance duration, stride length [1, 2], and ground reaction forces [3]. Close symmetry of gait measurements from the separate legs is considered normal. Therefore, any asymmetries constitute gait dysfunction and are most commonly identified as a limp. Gait asymmetries correspond with an increased risk of falls, physical disabilities, or psychological and secondary medical problems [4].

Since gait asymmetries may lead to disastrous outcomes, clinical focus has been placed on correcting gait. One population of interest for gait correction is amputees. Prosthetic gait is typically asymmetric and has been shown to be associated with increased rates of arthritis in lower extremities [5]. In addition, in 2005 there were 1.0 million lower-limb amputees with the number expected to rise to 2.4 million by 2050 [6].

1.1 Previous Work

This work details the design, improvement, and testing of a rehabilitative device for gait correction implementing real-time feedback methods – the Adaptive, Real-Time Instrumentation System for Tread Imbalance Correction (ARTISTIC) 2.0. Design of the original ARTISTIC device was inspired by the Lower Extremity Ambulation Feedback System (LEAFS). Both devices, LEAFS and ARTISTIC focused on providing rehabilitative feedback cues through portable devices.

The original ARTISTIC device integrated instrumented insole technology with a smartphone through wireless communication. The system was capable of measuring and recording stance times of an individual during normal walking activities. The smartphone provided feedback cues through visual, auditory, and vibrotactile modes. The purpose of the feedback cues was to assist in correcting asymmetric gait patterns. The ARTISTIC device was validated through a human subjects test [7].

1.2 Contributions

One of the significant contributions of this work was upgrading the hardware of the previously designed ARTISTIC device. Improvements were made with respect to the specific electronics hardware used and how that hardware was oriented in the device. Such improvements were targeted at making the ARTISTIC 2.0 a more viable device for at-home rehabilitation.

Another major contribution was a redesign of the auditory and vibrotactile feedback modes. Since most subjects from the previous ARTISTIC device testing preferred the visual mode of feedback, much of the efforts from this work were focused on providing more intuitive auditory and vibrotactile feedback. The auditory feedback was improved by creating prompting tones that were uploaded to the Android smartphone app and played back using a specific algorithm. The vibrotactile feedback was improved by installing vibrating motors in the insoles and communications box of the device. Motors vibrated according to the same algorithm as the auditory feedback.

This work also focused on a complete redesign of the application that subjects interact with on the Android smartphone. Effort was made to create an application that had a natural flow from screen to screen. The goal was to not only make the feedback modes intuitive, but also the smartphone application itself. An intuitive application makes use of the ARTISTIC 2.0 device in at-home rehabilitation more plausible. Individuals without a technical background or little experience using smartphone devices can understand and interact with the application. In addition, the structure of an SQLite database was designed for persisting data captured by the ARTISTIC 2.0. Although the database did not go live as a part of this work, the foundation has been laid for it to be a part of the next iteration.

1.3 Hypothesis Tested

The above contributions sought to improve the ARTISTIC 2.0 with a specific focus on making feedback more intuitive. Therefore, the following hypothesis were tested:

- **Hypothesis 1** states that gait symmetry of subjects tested using the ARTISTIC 2.0 device will be altered by one or more feedback modes or by a combination of feedback modes. If the feedback modes are intuitive, subjects will be able to modulate their gait symmetry, in either a positive or negative direction. This hypothesis will be tested through human subject testing with the ARTISTIC 2.0 and post-analysis of resulting gait symmetry patterns.

- **Hypothesis 2** is that subjects will select a preferred feedback mode, though the preferred mode may not correspond with the most effective mode in altering that subject's gait symmetry. If the feedback modes are intuitive, the subjects will perceive a preferred feedback mode as being most effective in altering their gait symmetry. This hypothesis will be tested through a questionnaire completed by subjects immediately following their testing with the ARTISTIC 2.0.

Verification of the ARTISTIC 2.0 device was carried out in the Motion Capture Laboratory of the Department of Physical Therapy, University of Utah. This verification process was important to demonstrating the reliability of the ARTISTIC 2.0 device as a rehabilitative device. To validate the ARTISTIC 2.0 device in a clinical setting, testing was conducted on the device among a prosthetic subject population at the Physical Medicine and Rehabilitation Outpatient Clinic (PM&R), University of Utah.

1.4 Overview

In Chapter 2 a discussion of studies and work relevant to the content of this thesis is presented.

In Chapter 3, a draft manuscript is included that will be submitted to the Pervasive and Mobile Computing journal in September 2012. The manuscript describes the detailed design of the ARTISTIC 2.0 insoles and communications box, Android application, and feedback modes. It also presents results of the verification study against current clinical equipment in the Motion Capture Laboratory and the clinical testing performed in the PM&R Clinic. The manuscript concludes with future work and revisions to be made to the system.

In Chapter 4, conclusions from this thesis are provided and recommendations for future work are discussed.

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CHAPTER 2

BACKGROUND

A number of studies have investigated the effects that gait asymmetries may have on individuals with prosthetics. These studies provide insight into the importance of correcting asymmetric gait patterns in any individual. While this work focuses on prosthetic gait, many of the hypothesis and conclusions are general and may be extended to individuals with other gait patterns.

2.1 Effects of Asymmetric Gait

One study showed that above-knee amputees experienced osteopenia or osteoporosis significantly more in the amputated limb compared with the intact limb [1]. A clinical and radiological survey of lower limb amputees reported a significant increase in osteoarthrosis in the intact knee and osteoporosis in the amputated limb. Backaches were also reported by nearly half the subjects and more than half suffered from scoliosis [2].

A study of veterans from the Second World War investigated the effects of long-term prosthetic use. The discovery was that use of a prosthetic for many years is associated with increased risk of hip osteoarthritis in both the amputated and intact limbs [3]. Another study of veteran traumatic amputees discovered that pain and disabilities in amputees was not limited to the amputated limb [4]. Subjects of this study who had an amputation experienced pain in their intact knee at more than twice the rate of those without an amputation.

Yeung and Leung studied effects of long-distance walking on trans-tibial amputees [5]. The study specifically investigated changes in spatial, temporal, kinetic, and kinematic gait parameters. Following a 30-minute walking session, it was found that intact limb propulsive force and dorsiflexion were significantly reduced. Subjects spent more time in stance phase on the intact limb and displayed higher ground reaction forces for the intact limb. This study suggests that fatigue occurs in the intact limb that can lead to changes in gait pattern.

Tesio et al. conducted a study to examine the center of gravity of healthy subjects as compared to above and below knee amputees [6]. Kinematics of the amputees were found to be acceptable. Yet good kinematics concealed severe asymmetry of kinetic variables, specifically overloading of the intact limb and under loading of the prosthetic limb.

Information obtained by tracking the gait of individuals who display asymmetric patterns can be fed back to the individual to encourage improvements in gait. This process of tracking gait and providing feedback is a closed-loop feedback method to resolving gait asymmetries. The work presented in this thesis is a closed-loop feedback method using real-time tracking for gait rehabilitation.

2.2 Gait Retraining Devices

Various assistive devices have been proposed to aid in the rehabilitation of asymmetric gait. Most devices aim to provide the individual with some form of feedback to assist with changing gait towards normal. Historically these systems are large, expensive, and complicated.

Darter and Wilken designed a virtual reality-based feedback system for gait rehabilitation of transfemoral amputees [7]. The system was intended to reduce metabolic costs through visual feedback via a computer-generated environment. Subjects displayed improvements in gait kinematics.

Ridge and Richards used a series of Eagle Digital Motion Analysis Cameras to collect data and provide visual feedback regarding walking velocity during gait analysis [8]. Subjects walked down a hallway with a screen at the end. Information about walking velocity was projected on the screen in real-time. Subjects were able to monitor their velocity through the cues on the screen. The result was that subjects were able to maintain a preferred velocity during 90.6% of the trials by following the information on the screen.

Eriksson et al. investigated the effects of visual and auditory feedback on running techniques of well-trained athletes [9]. Auditory feedback was provided through a wireless headphone set with the volume being proportional to the error. Visual feedback was provided through a TV-monitor placed in front of the runner and displayed as a series of bars. Findings indicated that auditory feedback worked better than visual feedback.

A group from Stanford University has worked towards making an effective system to provide haptic feedback for gait retraining [10-12]. The system uses Vicon 3D motion capture and an instrumented Bertec treadmill to interface with software meant to provide real-time feedback. A combination of two vibration devices, one skin stretch device, and an audio metronome were found to be intuitive for the subjects to use. The haptic feedback system was effective in reducing knee adduction moment and altering gait patterns in less than 5 minutes. The success of such haptic feedback in altering gait encourages further research into using haptics as a viable form of gait feedback.

Hidler et al. created the overground gait and balance training system for severe gait impairments [13]. The system consists of a harness device controlled by electric motors mounted to a carriage that slides along rails on the ceiling of a rehabilitation clinic. Though the system is effective in providing a means for practicing gait training during acute stages of injury, it is impossible to use outside the clinical setting.

Feasel et al. integrated a virtual environment with an instrumented treadmill and Vicon motion capture system into a novel adaptive speed control system called the IVERT [14]. Feedback was provided to test subjects visually through the virtual environment and proprioceptively through changes in treadmill belt speeds.

2.3 Mobile Devices

The devices and techniques described above were effective in altering gait. Yet these devices are large, expensive, and difficult to use. Since the number of people seeking gait rehabilitation is high, there is a need for systems that are inexpensive and mobile. Smaller, simpler devices that can be sent home with a patient have the potential to improve the rehabilitation process.

A home-based monitoring and intervention system was designed by Mirelman et al. to use audio-biofeedback [15]. The system was validated with a Parkinson’s Disease subject population. The study used both positive and negative feedback. The former being used to inform of error and the latter to inform of success. Small but positive changes were observed in postural control among the subjects. Improved mood was also reported by the subjects and was hypothesized to represent a feeling of accomplishment.

One move towards inexpensive and easy to use motion analysis technology was a study conducted by Clark et al. [16]. The study examined the reliability of using Nintendo Wii Balance Boards as substitutes for force plate technology. The system developed by the investigators proved reliable for measuring weight bearing asymmetry and center of pressure path velocity. Since millions of Wii Balance Boards have been sold world wide, this technology may be a reasonable alternative for motion labs. It is also a positive move towards inexpensive and portable motion analysis technology.

Another move towards mobile rehabilitation devices was proposed by Bae et al. with the Smart Shoes system [17]. The Smart Shoe design, coupled with a proprietary touch screen microprocessor for data analysis and storage, was proposed as a mobile gait monitoring system. The Smart Shoe uses an air bladder sensor embedded in a shoe insole for pressure measurements. The air bladders were connected to the data acquisition board, which was then connected to a laptop computer.

A software program was developed in Matlab for analysis of data extracted from an accelerometer to determine gait patterns [18]. The system, iGait, can be used to determine 31 gait features from data captured by an accelerometer mounted to the lower back of the participant. Results are displayed on a computer screen in real-time and data are stored for further postprocessing and statistical analysis. The system requires a computer running the Matlab program and is therefore not completely mobile.

Chelius et al. created a mobile gait monitoring system that was tested for six days in a rugged environment [19]. The system consisted of FSR and IMU sensors transmitting data wirelessly to a database. Although technical problems limited the amount of data recorded, a substantial amount of high quality data were stored and the system held up over the test period.

Hausdorff et al. demonstrated that for less than $50 an accurate footswitch may be built to measure temporal parameters of gait [20]. The system consisted of two 1.5” square force sensitive resistors (FSR) taped to an insole and wired through simple circuitry and a 9 V battery. Footswitch estimates of heel contact and toe-off times identified stance duration to within 3% error as compared to force plate determined data. Swing and stride duration were estimated within 5% error of the force plate values.

Various studies have investigated use of FSRs as gait measurement sensors [21-25]. To demonstrate reaction properties of these sensors an evaluation of commercially available FSRs was completed using dead-weight tests and hysteresis tests [26]. It was found that for dead weight tests of 4-minute durations, the Interlink FSR drifted between 3.05% - 12.37%. Hysteresis of the Interlink FSR was low comparative to other FSRs. Resistance in subsequent force peaks remained relatively constant for the Interlink FSR. The conclusion of the evaluation was if large forces were to be applied at high frequencies, the Interlink FSR was among the preferred choices.

2.4 Feedback Methods

A number of feedback modalities, including visual, auditory, and haptic, may be used to relay information to an individual about their gait. To understand responses to feedback stimuli it is important to understand how those stimuli are received by the human body. The perceptual system processes feedback stimuli as conscious and subconscious information. The subconscious dorsal stream is important for motor control

[27]. Therefore, feedback must be designed to communicate with this subconscious stream.

Auditory reaction time is faster than visual reaction times and should be explored as a viable form of feedback [9, 28]. Open-loop auditory feedback can be as simple as sending a feedback signal at a rate that is selected before testing begins, similar to using a metronome. Such methods of feedback have been used for gait correction in other studies [29-31]. This form of open-loop feedback is prone to disturbances, inherently unstable, and its redundancy becomes less effective in arousing the perceptual process as testing progresses.

Closed-loop feedback requires sensing the subject's gait during testing and providing signals based on real-time results. The closed-loop method of feedback, generated by the subject's motion, has been shown to regulate and stimulate gait [32].

Baram and Miller investigated the effects of closed-loop auditory feedback in correcting gait in subjects with Multiple Sclerosis [33]. A motion sensor mounted to the subject's waist provided auditory cues based on the subject's movement. The subject was instructed to adjust gait in order to create rhythmic cues. Additionally, subjects were asked to walk with no feedback at the end of testing to explore the short-term residual improvements in gait from the feedback cues.

Results of this study were compared to results from a previous study by the same authors that investigated visual feedback [33]. It was found that visual feedback produced large improvements in stride length while auditory feedback produced greater improvements in walking speed. This may be due to visual feedback producing the effect of reaching a target or end-point for stride length. It also reinforces findings that reaction times for auditory signals are faster than those for visual signals. Relatively large short-term residual improvements were also noted in each subject when the feedback was turned off.

Roerdink et al. investigated the effects of acoustic rhythms in gait rehabilitation [34]. Findings were that it took about four steps for subjects to attune their steps to the beat of a metronome rhythm. The transient period must be taken into account when evaluating the effect of acoustic pacing in gait training. This suggests that previous studies on the effects of acoustic pacing in gait training may have underestimated improvement if they did not account for the transient period. Furthermore, it was found that there is a natural tendency for footfalls to precede metronome sounds.

Haptic feedback is believed to provide better subjective estimation of movements than visual feedback [35]. An overwhelming majority of proprioception, tactile, and force feedback literature is focused on upper extremities. However, some studies of haptic feedback to improve gait have provided insight into using haptics as a plausible form of feedback.

Koritnik et al. compared visual and haptic feedback methods using expensive haptic equipment called the Lokomat, an actuated gait orthotic [36]. During visual feedback subjects followed an avatar of themselves projected on a screen to create a virtual mirror of their movements. During haptic feedback the subjects were attached to the Lokomat and guided in their movements by impedance-based control. The study found that haptic feedback alone resulted in better tracking than visual feedback alone. A combination of haptic and visual feedback provided the best results for tracking.

A haptic design to provide sensory information for individuals with lower-limb prosthesis was designed by Fan et al [37]. The device was designed to improve functionality and aid in trauma rehabilitation. The system consisted of balloon actuators placed on the posterior, anterior, medial, and lateral parts of the subject's leg. The actuators were inflated to provide directional cues. Subjects were able to differentiate directional stimuli and inflation patterns with greater than 94% accuracy. The results suggest that simple haptic stimuli can relay complex messages.

Effenberg took ground reaction forces from a subject jumping on a force plate and mapped them to an electronic sound with amplitude and frequency representing force magnitude and duration respectively [27]. The first subject's jumps were used as a model for all subsequent subjects to mimic. Subjects were then provided auditory, visual, and combined audiovisual feedback as they tried to match the jumping height of the model. Results showed that combined audiovisual feedback helped achieve greater accuracy in 30 out of the 40 subjects. However, only 15 of the 40 subjects subjectively judged the combined audiovisual mode of feedback to be the best. This suggests that although combined feedback modalities may be the most effective for improving motor control, these modalities may not be perceived as the best by the end user.

2.5 Interactive Rehabilitative Methods

Recently, video games have been investigated as educational tools. Dondlinger completed a literature review on educational video game design [38]. The literature agrees that certain factors are important in stimulating learning: narrative context, rules, goals, rewards, multisensory cues, and interactivity. An interactive rehabilitative device that uses the factors above has the potential to improve the overall quality and speed of gait rehabilitation.

Schwabe and Goth designed a game for mobile PDA handheld computers [39]. The purpose of the game was to learn about resources on a university campus in the shortest amount of time. The game involved rules, goals, feedback, outcome, conflicts and competition, and interaction. The authors concluded that mobile learning offered a mixed reality environment that fosters high motivation to learn. Mixed reality environments augment learning more than purely physical or purely virtual environments are capable.

Investigation has been made into using Nintendo Wii Sports and Wii Fit games for rehabilitation of stroke patients [40]. Selected games were assessed by two rehabilitation therapists, each with more than 15 years of experience in motor learning. Therapist assessments were that Wii games could be used as a rehabilitation aid, but that further research should be conducted into developing games specific for rehabilitation use.

Feeling involved during the rehabilitation process is important to many patients and can improve their perception of quality of care. A questionnaire was developed to gauge patient perception of gait and motion lab visits as a part of rehabilitation [41]. The questionnaire was aimed at discovering if first time patients felt the gait lab sessions were useful and whether patients felt that being observed was unsettling in any way. Participating patients perceived an improvement in the quality of care and a better understanding of what to work on during their rehabilitation process.

2.6 Previous Work

The Lower Extremity Ambulation Feedback System (LEAFS) was created to provide inexpensive, real-time gait feedback through a system that is intuitive and interactive [25]. It was designed to be an alternative option for persons without access to a motion analysis lab. The sensing part of the system consisted of a matrix arrangement of FSR sensors embedded in a silicone insole. Data from the sensors were transmitted wirelessly to a netbook and processed using Matlab. Electronics and the power supplies for the system were contained in a pack worn on the waist of the user. The system was lightweight, inexpensive, wireless, and easy to manufacture for a clinical environment.

In a validation study, the LEAFS provided real-time auditory feedback to individuals with lower limb amputations [25]. Subjects were able to improve gait asymmetry while using the LEAFS. It was also shown that the stance ratio determined by LEAFS had a strong correlation to data from a motion analysis lab.

Since LEAFS used a netbook, it was portable but not fully mobile because it could not be easily used outside a clinical setting or at-home rehabilitation. A truly mobile gait rehabilitation device, providing various modes of real-time feedback, was needed. This motivation brought about the development of the Adaptive, Real-Time Instrumentation System for Tread Imbalance Correction (ARTISTIC) and ARTISTIC 2.0.

Design of the ARTISTIC device focused on creating a truly portable device with various feedback modes [23]. As such, the ARTISTIC insole was simplified to two 1.5" FSR sensors, one oriented beneath the toes and one beneath the heel. The reduced number of sensors in the insole increased the sampling rate of the data while decreasing the required processing power. Other hardware improvements included using an Arduino Mini Pro microcontroller with faster clock speed than the LEAFS microcontroller and converting from XBee serial transmitters to Bluetooth modems for wireless communications.

Perhaps the biggest improvement was that ARTISTIC used a smartphone rather than a netbook to receive wireless messages from the insoles and communicate feedback [23]. Use of an Android smartphone made ARTISTIC a mobile device that could be accessible to large populations at relatively low costs. Additionally, the smartphone is a system with built-in functionality for providing different feedback modes. It was not necessary to build proprietary hardware to provide feedback.

Testing was conducted using the ARTISTIC device among a population of subjects with healthy gait [42]. The primary goal of testing was to determine whether the ARTISTIC device was capable of altering healthy gait through visual, auditory, or vibrotactile feedback modes. The testing also included a questionnaire about preferred feedback methods. Results of the testing were that subjects were able to alter gait parameters according to the sensory feedback. The majority of subjects preferred the visual feedback to the auditory or vibrotactile feedback.

The previous version of the ARTISTIC placed all circuits and power supplies in a microcontroller box mounted to the subject's ankle [42]. The resulting box weighed 103 g, which may have been a contributor to a large variance in gait ratios between control subjects. The only sensors used in the previous ARTISTIC were FSRs. These were uncalibrated and used as switches, so the only gait parameter measured by the previous ARTISTIC device was stance time.

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CHAPTER 3

A MOBILE GAIT TRAINING SYSTEM PROVIDING REAL-TIME FEEDBACK THROUGH SMARTPHONE TECHNOLOGY

Matthew Schmidt, Avery Johnson, Spencer Thompson,
Colby Hansen, and Stacy Morris Bamberg

Department of Mechanical Engineering, University of Utah

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3.1 Introduction

Gait rehabilitation is used to eliminate or reduce gait pathology. An asymmetric gait that remains uncorrected has the potential to cause balance impairment, metabolic costs, osteoarthritis, and lower back pain. Gait rehabilitative methods tend to be highly specialized for the individual patient [1], causing a high resource demand throughout rehabilitative therapy. Current equipment used for real-time gait retraining is typically large, stationary, and expensive [2-4]. Due to high demands for personnel and equipment during rehabilitation, many efforts have been made to design more mobile gait rehabilitation devices [5-7].

Embedded system technology has allowed for the creation of body-wearable sensor networks for remote health and activity monitoring. These networks have the potential to enhance quality of life, facilitate independent living, and reduce rehabilitation resource demands [8]. Smartphone and tablet technology is becoming increasingly pervasive as more devices are introduced to the market. There is a need for systems that connect body-wearable networks with the processing power and storage capacity of mobile devices such as smartphones and tablets.

3.1.1 Motivation

The need for an inexpensive, truly mobile gait rehabilitation device spurred the development of the Adaptive, Real-Time Instrumentation System for Tread Imbalance Correction (ARTISTIC). This device interfaces body-wearable embedded systems with smartphone technology. One of the primary goals of this device was to provide three different modes of real-time feedback (visual, auditory, and vibrotactile) about gait symmetry through a smartphone application (app) [9]. The first design of the ARTISTIC was validated in a study of subjects with healthy, normal gait. The majority of subjects from the study preferred the visual feedback mode and all subjects were able to significantly alter their gait in response to the visual feedback [10]. The auditory and vibrotactile feedback modes were perceived as difficult to use. These modes provided only a binary reactive response indicating whether the prior two steps were above or below a specified symmetry threshold. Furthermore, it was reported that the communications box attached to the subject's ankle was heavy and caused discomfort. The first design was also limited to measuring only stance time characteristics.

This paper presents development of the revised ARTISTIC device that implements proactive auditory and vibrotactile (haptic) feedback modes. The system incorporates a tri-axial accelerometer and gyroscope to measure and analyze more gait parameters simultaneously. System verification against current clinical gait measurement technology is provided. Findings from a validation study involving subjects with prosthetic gait are also presented and discussed.

3.2 Novel System Design

The ARTISTIC design was revisited and critical changes were made in all aspects of the design. The next sections discuss design improvements in the device hardware and software. In this paper, the revised version will be referred to as ARTSITIC 2.0.

3.2.1 Hardware

The ARTISTIC 2.0 hardware consists of three primary components: an instrumented insole, a communications box, and a smartphone. Design priorities for each component included keeping the system simple, intuitive, inexpensive, and robust.

3.2.1.1 Instrumented Insole

Previous designs of instrumented insoles involved an array of force sensitive resistors (FSRs) embedded in silicone with other electronics housed in a separate container or box [9]. Our novel insole design embeds an inertial measurement unit (IMU) and a microprocessor in addition to FSRs as shown in Figure 3.1.

Since FSR responses vary depending on the value of the resistor in their voltage divider circuit [11], two 1.5” square FSRs (Interlink Electronics, Camarillo CA) were stacked in the toe and heel regions of the insole to track different types of data. One FSR in the toe and one in the heel made up a pair. One pair of FSR voltage dividers used 5kΩ resistors to capture heel-down and toe-off characteristics like a footswitch [12]. The other pair used 1kΩ resistors to take readings with more resolution to be used in determining plantar pressure [11].

Previous studies using an IMU for gait measurement placed the IMU on the back of the shoe or in a separate box [13, 14]. Two problems arise from positioning the IMU like this. First, the box is rigidly mounted to the shoe and is difficult or impossible to use on other shoes. Second, excessive movement not associated with the actual gait is recorded by the IMU, making it more difficult to go from acceleration to position. Here, the IMU, a combination board of an ITG3200 gyroscope (InvenSense Inc, Sunnyvale, CA) and an ADXL345 accelerometer (Analog Devices, Norwood, MA), was embedded in the insole to reduce noise and to simplify transfer of the system to different shoes.

An Arduino Pro Mini microcontroller (Sparkfun Electronics, Boulder, CO) with ATMEGA 328 (Atmel Corp, San Jose, CA), 8MHz microprocessor was used to sample data. Since the Arduino needed to connect to FSR, IMU, Bluetooth, and vibro motor components, embedding the Arduino in the insole reduced wire lead lengths. It also reduced connections that could be severed by repetitive flexion and pressure from the foot. To further reduce the number of wires and component sizes, a printed circuit board (PCB) was designed for the ARTISTIC insole. The Arduino, IMU, and PCB are depicted in Figure 3.2.

Embedded inside the insole is a VPM2 vibrating disk motor (Solarbotics, Calgary, Canada). This actuator can be used to deliver vibrotactile haptic feedback. The motor is connected to a digital output pin on the Arduino.

3.2.1.2 Communications Box

The instrumented insole requires power and a means of data transfer from the Arduino to the Android smartphone. The insole is connected to the communications box, which transmits data wirelessly using Bluetooth protocol. To provide power, the communications box houses a rechargeable 3.7 Volt battery providing 1500 milliamp hours of power. For data transmission the communications box includes a Bluetooth Mate Silver Class 2 Bluetooth modem (Roving Networks, Los Gatos, CA), transmitting at 57.6 kbps. The Bluetooth Mate Silver consumes about 50 milliamps when transmitting data and only 25 milliamps when idle, regardless of the connection status [15].

To simplify connections between the Arduino and Bluetooth Mate, a PCB was also designed for the communications box. The PCB is shown in Figure 3.2 with a Bluetooth Mate mounted to it. The communications box included a VPM2 motor identical to the one embedded in the insole. This motor is also connected to a digital output pin on the Arduino through the PCB board. The purpose of placing a motor in the communications box is to provide haptic feedback to individuals who cannot feel an insole vibration because they have prosthetic feet or suffer from peripheral neuropathy. The assembled communications box is shown in Figure 3.3.

Key improvements in the communications box and ARTISTIC 2.0 system as a whole are presented in Table 3.1. Weight and volume of the communications box decreased while number of sensors, data rate, and power supply were significantly increased.

3.2.1.3 Smartphone

It is projected that nearly 1 billion smartphones will be in use worldwide by 2015 [16]. Additionally, use of tablets and similar devices running on smartphone platforms is on the rise. Therefore, it is not unreasonable to propose a smartphone-driven rehabilitative device, because patient access to a smartphone, or smart device can be generally accepted. The ARTISTIC 2.0 uses a Samsung Nexus S smartphone (Samsung, Seoul, South Korea) running the Android 2.2 platform (Google, Mountain View, CA). The Nexus S has a 1 GHz processor and 16 GB of internal memory. It is important to note that each smartphone running an Android platform will have unique processor and storage specifications dependent on the manufacturer and model. An Android smartphone was selected as the platform for development because Android follows the Open Handset Alliance, allowing for unrestricted development on any Android device.

3.2.2 Software

Data transmission between the Arduino microcontroller and the Android smartphone required software development in two different environments. Processing the data from the IMU required development of a Java library to be run on the Android smartphone.

3.2.2.1 Android

An extensive Java based application (app) was developed for the ARTISTIC 2.0. The app utilized the computing power of the Android smartphone to take in large amounts of raw data, process them, and provide feedback to the user.

To interface between the Arduino and Android, ARTISTIC 2.0 used an open-source toolkit developed by Bonifaz Kaufmann called Amarino [17]. This toolkit provided an Android app and an Arduino library to make interfacing simpler for developers by providing pre-written code to run the Android-Bluetooth protocols.

The ARTISTIC 2.0 app received Bluetooth signals at 180 Hz (two signals, one from each limb at 90 Hz). Each signal contained 11 different data points. The Android thus processed over 1900 individual data points per second. Raw data were used to calculate important gait parameters and also stored for postprocessing. Data were stored and retrieved as text files using the internal storage techniques native to the Android platform. Feedback was provided through the smartphone based on the gait parameters calculated during on-phone data processing. A visual representation of data handling on the smartphone is given in Figure 3.4.

3.2.2.2 Arduino

The Arduino integrated development environment utilizes C++. An infinite loop was created to poll all sensor readings, measure the time to complete polling, and transmit readings through the Bluetooth modem as concatenated strings. The loop also contained a function that would listen for a message from the Android with instructions to send signals to the VPM2 motors in the insole or communications box. Data transmission through the Bluetooth modem was accomplished using the MeetAndroid library, which is part of the Amarino toolkit [17]. Sensor polling and data transfer are shown in Figure 3.5.

3.2.2.3 IMU – Java library

To work with the data from the IMU and compute the stride length, a Java library was developed for use in the Android app. Functions within the library read in the data from a walking test, identified the important markers from each step, and calculated the average distance travelled for each step from toe-off to heel-down.

3.3 Methods

Data obtained from the FSR and IMU sensors were processed on the phone to compute gait characteristics of stance time, symmetry ratio, and stride length. Resulting values were used to provide feedback to ARTISTIC users.

3.3.1 Sensors

3.3.1.1 Force Sensitive Resistors (FSR)

Voltage changes across the FSRs were sampled by the Analog to Digital converter (ADC) on the ATMEGA328 chip. The ADC had 10-bit resolution. The resulting digital output values were used to analyze stance time and symmetry ratio measurements. With no weight on the insole the FSR output values typically have a non-zero bias. This bias is a reflection of pre-loading on the FSRs, e.g., caused by the tightness of the shoe on the foot. The bias varies each time the ARTISTIC is setup. Therefore, a calibration routine was included in the Android app to “zero” the output values. To determine gait flags such as heel-down or toe-off, a threshold for the output values was set for each FSR as follows

$$GaitThreshold = 0.5 * (MaxValue_{FSR} - Bias_{FSR}) + Bias_{FSR} \tag{1}$$

The algorithm used by ARTISTIC 2.0 to determine stance time is outlined in Figure 3.6. Stance time on the ARTISTIC 2.0 is defined by the equation below

$$t_{stance} = t_{toe\_off} - t_{heel\_down} \tag{2}$$

Stance time for each foot was used to compute gait asymmetry. There are several methods to compute gait asymmetry [18]. The method selected for ARTISTIC 2.0 is the symmetry ratio

$$Symmetry\ Ratio = \frac{t_{paretic}}{t_{non\_paretic}} \tag{3}$$

where $t_{paretic}$ represents the stance time of the less favored limb, a prosthetic limb for example, and $t_{non\_paretic}$ represents the intact or favored limb. To make the symmetry ratio simpler, the ARTISTIC 2.0 algorithm ensured that the numerator was always the lesser of the two stance time values. A negative sign was used to indicate asymmetry favoring the left leg and a positive sign indicated asymmetry favoring the right leg. It was possible for the symmetry ratio to change from positive to negative within a single trial. This also made statistical analysis more powerful because the ratio was no longer skewed by values > 1.0 [18].

3.3.1.2 Inertial Measurement Unit (IMU)

The tri-axial accelerometer and gyroscope on the IMU communicate with the Arduino through I^2C protocol. The accelerometer was set at ±2*acceleration of gravity (*g*) along each axis with a sensitivity of 256 LSB/*g* and the gyroscope has a range of ±2000°/sec with a sensitivity of 14.375 LSB per °/sec. Both were sampled by the ADC, which has 10-bit resolution.

There are two coordinate systems used for computation of the IMU data as shown in Figure 3.7. The first is the global reference frame where the user is walking. The second is the body frame, which is the frame of the insole itself, where the IMU is mounted. The body frame reflects the orientation that the sensors are reading within. In order for the stride length to be calculated, the acceleration readings need to be transformed from the body frame into the global frame.

To simplify and speed up computation, movement of the foot was assumed to occur only in the X-Z plane with rotation occurring only about the Y-axis in the body frame. Subjects were instructed to walk in a straight line. A previous study under similar conditions found that the angular velocities about the Z and X-axis and the acceleration along the Y-axis were much lower, making this a reasonable assumption for stride length estimation [14]. Rotation matrices were used to transform the readings from the body frame to the global frame. To compute the rotation matrices, the rotational velocity about the Y-axis of the body was integrated to get an angle of change at each time step. The equation used is

$$\theta_{i+1} = \left[\frac{(\omega_{i+1} + \omega_i)}{2} \times (t_{i+1} - t_i)\right] + \theta_i \tag{4}$$

After determining the angle of rotation at each time step a rotation matrix was computed and used to transform the acceleration reading in the equation

$$\begin{pmatrix} X_{Global} \\ Y_{Global} \end{pmatrix} = \begin{bmatrix} COS(\theta) & SIN(\theta) \\ -SIN(\theta) & COS(\theta) \end{bmatrix} \begin{pmatrix} X_{Body} \\ Y_{Body} \end{pmatrix} \tag{5}$$

Because of the inherent drift in both the accelerometer and the gyroscope, Zero Velocity Updates [19] were incorporated using the cyclic nature of walking. The bias was updated during a detection period of zero velocity, after the acceleration due to gravity was removed. The zero velocity period of a step was identified when both the heel and toes sensors register force indicating that the foot is in contact with the ground. The gravitational acceleration was removed and the remaining acceleration readings during this time were taken as the bias of the accelerometer giving a bias for each axis to be taken into account over the next step. To further improve upon the bias updating, the functions use not only the bias at the beginning of a step but also the end of the step allowing for a linear bias adjustment over the time of the stride.

To detect when the foot is at rest (zero velocity) or when the foot is inswing, the FSR readings are used along with calibrated threshold of the FSRs to find the heel-down, toe-down, heel-off and toe-off gait flags. With these points identified for each step, the bias update can take place from toe-down to heel-off followed by the double integration of the acceleration between toe-off to the next heel-down . The equation used for integration is

$$v_{i+1} = \left[\frac{(a_{i+1}+a_i)}{2} \times (t_{i+1} - t_{i)}\right] + v_i \qquad (6)$$

A diagram of how the IMU data are processed is shown in Figure 3.8.

3.3.2 Feedback

The gait characteristics measured by ARTISTIC 2.0 are relayed to the user through three feedback modes. Each mode was designed to be simple to interpret by the senses it targeted.

3.3.2.1 Visual Feedback

The user interface for ARTISTIC 2.0 visual feedback provides graphical and numeric feedback to the user, as seen in Figure 3.9. Two vertical gray lines indicate an acceptable gait range (+0.8 to -0.8 with 1.0 at the center). This gait range is a variable that can be set as a target zone for the user to achieve depending on the severity of the user's gait asymmetry. A third vertical line, the "gait marker", indicates the user's current symmetry ratio and is updated each time a step is taken. If the current symmetry ratio falls within the acceptable gait range the gait marker is displayed in green. When the symmetry ratio leaves the acceptable gait range the gait marker is displayed in red. Gait marker placement to the left of the gait range lines indicates more time spent on the left leg. Placement to the right indicates more time on the right leg.

The symmetry ratio is displayed numerically at the bottom of the screen. Positive and negative signs are not displayed here to reduce confusion about meaning of the signs.

Indication of direction for asymmetry is delivered through location of the gait marker instead.

Movement of the gait marker is intuitive because its position corresponds with the leg that is being favored and it provides negative feedback when the marker turns red. Numeric values are easy to interpret because they tend towards 0.0 as gait becomes less symmetric and towards 1.0 as gait symmetry improves.

3.3.2.2 Auditory Feedback

To ensure that users do not depend on any visual cues during auditory feedback, the smartphone screen displays a static image and static message on a black background, as seen in Figure 3.9. ARTISTIC 2.0 auditory feedback is provided as a melodic tone played through the smartphone speakers. Headphones can also be worn to receive auditory feedback.

It is believed that reaction times to auditory stimulus are faster than reaction times to visual stimulus [20, 21]. Most studies on auditory feedback use either a pre-selected metronome speed or a subject-preferred speed, based on the most comfortable walking pace for the subject, in an open-loop feedback model [22-24]. However, closed-loop feedback has been shown to regulate and stimulate gait improvements more than open-loop feedback [25].

Design of the ARTISTIC 2.0 auditory feedback targeted a closed-loop method. The continuously updating metronome is dictated by an average of the previous 10 stance times from both feet. The average stance time is used as the desired stance time for the next step. This makes the auditory feedback closed-loop as shown in Figure 3.10. A continuous average of stance times allows auditory feedback to update real-time to keep up with changes in the subject's gait such as increases or decreases in walking speed.

The auditory feedback played a tone during the final 300 milliseconds (ms) of the desired stance time. The moment at which auditory feedback began was calculated as follows

$$t_{tone\_start} = t_{heel\_down} + (t_{desired\_stance} - 300\ ms) \quad (7)$$

Repetitive auditory stimuli can become less effective in arousing the perceptual process over time [25]. To break up the repetitive nature of the auditory feedback, the first five tones from the diatonic scale of C are played as feedback tones. With each successive step the next tone in the scale is played, repeating the pattern every fifth step, thus creating a melody. The goal for subjects during auditory feedback is to keep the tones in rhythm by walking symmetrically.

3.3.2.3 Vibrotactile Feedback

The smartphone display during vibrotactile feedback uses the same static image and message used during auditory feedback (Figure 3.9). Vibrotactile is a form of haptic feedback. Studies have shown that haptic feedback results in better tracking and subjective estimation of movement than visual feedback [26, 27]. The ARTISTIC 2.0 vibrotactile feedback is provided by the VPM2 motors in the insole and communications box.

Vibrotactile feedback on the ARTISTIC 2.0 system uses the same timing algorithm as the auditory feedback for determining desired stance time and the start time of feedback cues. During the 300 ms of a vibrotactile feedback cue, the selected VPM2 motor vibrates. Toe-off should occur when the vibration ceases.

3.3.2.4 Stride Length Feedback

Stride length is computed at the conclusion of each feedback session on the ARTISTIC 2.0. This gives the user needed information to determine if their stride length should be adjusted during the next session. Implementing the stride length feedback at the end of the session does not interfere with needed smartphone resources, which could disrupt the time-sensitive feedback methods already discussed.

3.3.3 Subject Testing

Human subject testing was carried out to validate the ARTISTIC 2.0 device in a clinical setting. The testing protocol was approved by the University of Utah Institutional Review Board under the study no. IRB00053021. Ten subjects were recruited through the Department of Physical Medicine and Rehabilitation, University of Utah Hospital. All subjects had a lower limb prosthetic on one limb. The subjects were aged 48 ± 24 years. They were 5 feet 9 inches ± 3 inches tall and weighed 195 ± 46 pounds. Six of the subjects were male and four subjects were female. Six subjects had undergone an amputation of their right leg while four subjects had undergone an amputation of their left leg. Of those amputations, eight of them occurred below the knee while only two occurred above the knee. All subjects provided approved consent prior to testing.

Subjects were asked to participate in several short walking cycles during the course of testing. The testing protocol was designed to assess the ARTISTIC 2.0 system's ability to influence individual gait. Testing was also designed to determine the corresponding effectiveness of the visual, auditory, and vibrotactile feedback modes. Each subject was first introduced to the system and Android application interface. The subject was provided instructions on how to follow the different feedback cues and interact with the Android application. Installation of the ARTISTIC 2.0 was demonstrated and then subjects were instructed to install the system in their own shoes. Communication boxes, used to power the system and transmit wireless signals, were attached on top of the shoelaces with Velcro.

Following initial setup, each subject was asked to walk to the end of a 150-foot hallway and return to the starting point. The total distance walked was about 300 feet. During this baseline walk, no feedback was provided but data were collected on the Android smartphone for a control comparison with subsequent walks. After the baseline walk the subject completed three more walks of equal length to the baseline during which visual, auditory, or vibrotactile feedback cues were provided through the ARTISTIC 2.0. Selection of the feedback mode to follow was randomized using a balanced latin square. Upon completion of the three walks with feedback, the subject was asked to select two preferred modes of feedback. During a fourth walk the two preferred feedback modes were enabled in parallel to provide a combined feedback mode. Finally, the subject completed one more baseline walk with no feedback to assess whether any residual effects existed from the feedback modes.

After testing was complete, subjects filled out a questionnaire about their experience interacting with the ARTISTIC 2.0. The questionnaire was designed to gain insight into the possibility of the ARTISTIC 2.0 being used as a rehabilitative device that could be used outside a clinical setting. Subjects answered questions about their comfort level while wearing the device, their perceived stability during testing, and the efficacy of different feedback modes in altering their gait.

3.3.3.1 Statistical Procedures

Raw FSR data from each trial were analyzed posttesting to determine stance time, symmetry ratio, and stride length values. To determine the correlation between preferred feedback mode and changes in gait characteristics, the mean values from each subject's preferred feedback mode were compared against the control or first baseline walk using a two-tailed, paired student's *t*-test. Mean values from a feedback mode that produced the largest change in gait symmetry were compared to the control walk using the same two-tailed *t*-test. If the preferred method produced the largest change, the feedback mode that produced the second largest change was analyzed. Mean values from each subject's last baseline walk were also compared to their control walk using the same *t*-test. Based on results from the *t*-tests, p-values under 0.05 were considered statistically significant. Following the statistical tests, a post hoc power analysis was performed on the results of the *t*-tests. The post hoc powers are reported with the statistical results.

3.4 System Verification

3.4.1 Approach

To confirm the validity of the system, the ARTISTIC 2.0 was verified against equipment in the Motion Capture Laboratory of the Department of Physical Therapy, University of Utah. Motion capture in 3D was accomplished using a ten-camera Vicon motion analysis system (Centennial, CO) and two AMTI multi axis force platforms (Watertown, MA). Multiple sets of data were captured using the motion capture systems and the ARTISTIC 2.0 in parallel.

Verification of stance time measurements was accomplished by comparing stance times computed from the ARTISTIC 2.0 with stance times determined by pressure readings on the AMTI multi axis force platforms. Stance time on the ARTISTIC 2.0 were marked as FSR readings crossed threshold values set by an initial FSR bias reading, as described in Section 3.1.1. Stance time on the AMTI force platform was marked when pressure readings were non-zero. The AMTI force platform data capture rate was 1000 Hz. Time on the ARTISTIC 2.0 was recorded as time differences between data transmissions from each Bluetooth modem. Data were captured using both the 1kΩ and 5kΩ voltage divider circuits in the ARTISTIC 2.0.

To validate the stride lengths processed by the ARTISTIC 2.0, the stride length was first calculated using data from the motion capture system. To do this, the minimum value in the Z-direction reached by each step interval was determined. Then, using those times as the beginning and end of each step, changes in the X and Y-directions were used to determine the total change in position from each step. Computation of total change utilized the Pythagorean theorem. The IMU data were processed as described in Section 3.1.2.

3.4.2 Verification Results

Analysis of ARTISTIC 2.0 stance times showed that the system was capable of determining stance time within a 7.8 ± 1.0% difference from the force platforms if the system is utilizing the 5kΩ voltage divider circuit for FSR readings. Utilizing the 1kΩ voltage divider circuit results in a 13.5 ± 3.3% difference. The 5kΩ circuit is more accurate in determining stance time because its FSR readings respond quickly to pressure but also saturate quickly. Alternately, the 1kΩ circuit provides greater resolution in FSR readings as they correspond to foot pressure because it takes more pressure to saturate the readings. Both circuits were included in the ARTISTIC 2.0 design to provide for more flexibility in measurements. Results are presented in Table 2.

The stride length measurements from the Artistic 2.0 were evaluated using methods previously described. Stride length measurements were found to have an average error of -2.7 ± 6.9% as compared to the Vicon system. Results of the test are presented in Table 3.

3.5 Results

Subject testing of the ARTISTIC 2.0 was completed with ten subjects. During testing, data storage was inconsistent for three of the subjects. Therefore, test results were only analyzed for seven subjects. However, feedback modes functioned during testing for all ten subjects. As such, results of the usability questionnaire were reviewed for all ten subjects.

During testing, subjects reported an inability to perceive the vibrotactile cues. As a result, the last two subjects tested were not asked to walk with the vibrotactile feedback mode turned on. Analysis of stance time and gait ratio results excluded the vibrotactile datasets for all subjects except subject 7, who selected vibrotactile and auditory modes for the combined feedback trial.

Analysis to determine if the altered gait symmetry ratios were statistically different from the control is presented in Table 4. Average gait symmetry ratios over five trials are presented graphically for one subject in Figure 3.11.

Results of the post-testing questionnaire indicated that 40% of the subjects selected the visual feedback mode as their favorite, 30% selected auditory, and 30% selected combined auditory and visual. When asked if the feedback modes made a noticeable difference in their gait, 60% agreed that the visual mode was effective, 50% agreed that the auditory mode was effective, and 50% agreed that the combined auditory and visual mode was effective. Only 10% of subjects felt that their stability worsened while wearing the ARTISTIC 2.0, but 70% were willing to take the system home and wear it for up to three days.

Analysis of stride lengths showed that subjects took steps between 700mm to 1400mm long. Average stride length of an individual subject varied between feedback mode trials. An example of average stride lengths is provided for one subject in Figure 3.12.

3.6 Discussion

The ARTISTIC 2.0 system was effective in modulating the gait of subjects with a lower limb prosthetic during an extremely short training process as compared to normal gait rehabilitation. This result suggests that the system may be capable of positively adjusting the gait of a rehabilitative patient if used during more extensive and longer training periods. Use of the ARTISTIC 2.0 required little specialized training and all subjects agreed that they were able to walk and move normally with the system installed in their shoes. Post-testing surveys indicated that 80% of the subjects agreed that setting up the system on their own would not be difficult. This demonstrates that the ARTISTIC 2.0 is a simple, modular alternative to gait retraining using specialized equipment and environments. The system is also an economic alternative to more expensive gait analysis equipment, with an estimated prototype cost of US$345. It also indicates that the system is a viable option for at-home rehabilitation.

The *p*-values calculated indicate that what subjects selected as preferred feedback modes were effective in altering the gait symmetry of subjects. There was no preferred feedback mode that was an overwhelming favorite among the subjects. The preferred method selected by subjects did not correlate with the method that best altered their gait. This suggests that perception of an intuitive feedback mode is more influenced by individual preference than results of that feedback mode. Although subjects selected a preferred mode of feedback the majority of subjects also agreed that non-preferred feedback modes were effective.

Variance in gait symmetry ratio and stride length displayed an inverse correlation. As gait ratio improved, stride length decreased. This is an indicator that subjects began focusing more on following feedback cues and less on moving from one location to another. Furthermore, effectiveness of feedback cues can be determined, in part, by analyzing stride length during a feedback mode trial. If stride length decreases, the feedback mode likely interrupted the subject's perceptual process, which is the first step in providing feedback that works well with the senses.

One subject reported feeling that their stability worsened while wearing the ARTISTIC 2.0. In the posttesting questionnaire this subject stated that more practice with the combined visual-auditory mode could produce better results. This statement indicates that learning to follow the feedback cues was difficult for this subject and could have caused unstable gait.

Although the ARTISTIC 2.0 altered gait symmetry during a short testing period, the changes were relatively small. These findings correlate with those of the original ARTISTIC system that large permanent gait corrections must be made gradually [10]. This study was conducted among a small subject population but has built upon results from the previous ARTISTIC system. Testing needs to be completed with larger numbers of subjects interacting with the ARTISTIC 2.0 for a matter of hours or even days, preferably in the home environment. Further system improvements include installation of stronger vibrotactile motors in the communications boxes or embedded in the insoles that will be felt by subjects. This is necessary to be able to validate the vibrotactile feedback mode.

Another improvement is creating a more reliable connection between the communications box and insole. Wires and soldered connections were severed various times during subject testing, rendering subject data unusable. One possible alternative to these inconsistent connections is the long-term goal of embedding the system battery and Bluetooth modem inside the insole alongside the Arduino microcontroller and IMU. This would further simplify the ARTISTIC system as a whole, eliminating external wires and making system setup quicker.

During testing, the bias value of some FSRs had a tendency to drift either high or low. One possible cause of this drift is that silicone ran into the FSR pad while curing during manufacture of the insoles. Future revisions of the system should create a verification process to determine tendency of the FSR bias to drift in an insole.

System improvements also include changes to the Android smartphone application. For example, a SQLite database was developed to store raw values in real-time on the Android smartphone but was not successfully implemented during this study because it kept crashing the app due to the high storage volumes required every second. Optimization of the storage process should be assessed to implement this database in further revisions. Data capture through the app did not stop between tests, resulting in large amounts of data that were discarded posttesting. This data collection was using processing power unnecessarily. Later revisions of the application will eliminate periods of unwanted data collection and storage.

3.7 Conclusion

A mobile gait rehabilitation device using real-time feedback was developed for gait correction and training. The system was shown to record stance time and stride length with a maximum error of 17% as compared to equipment in a motion capture laboratory. The system was determined to be effective at altering the gait symmetry of subjects ambulating with lower limb prosthesis. Tests performed indicated that no single feedback mode was more effective than another. Instead, subjects identified with different feedback modes on an individual basis. The custom Android application, developed to process data and provide feedback, demonstrated its power as a mobile computing alternative to laboratory equipment or even laptop computers.

Use of this system may be extended to rehabilitation of subjects who have suffered from a stroke or Parkinson's disease. The system can serve as a supplemental rehabilitation device both in a clinical setting as well as for personal assistive healthcare. To further develop this device we will improve the vibrotactile feedback mode and make efforts to embed the power source and wireless communication board in the instrumented insole portion of the system.

3.8 Acknowledgements

The authors would like to recognize and thank C. Redd for his work and contributions in creating the original ARTISTIC system and for recommendations for improvement. The authors would like to additionally thank P. Dyer and K.B. Foreman for their consultation and assistance in the Motion Capture Laboratory, University of Utah.

3.9 References

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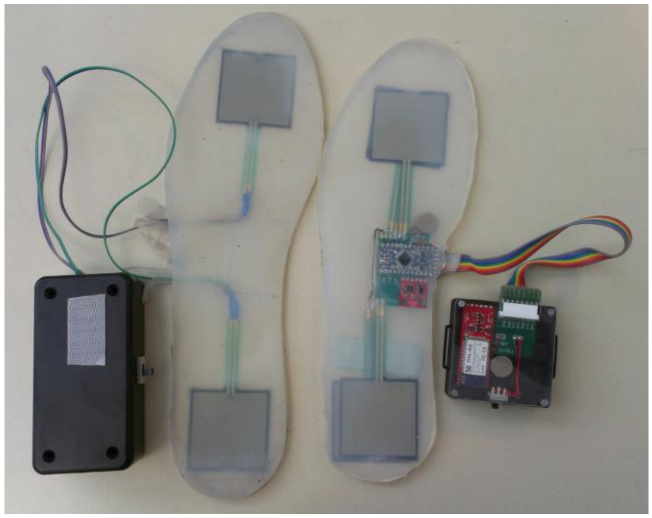

Figure 3.1: ARTISTIC and ARTISTIC 2.0 systems (left to right)

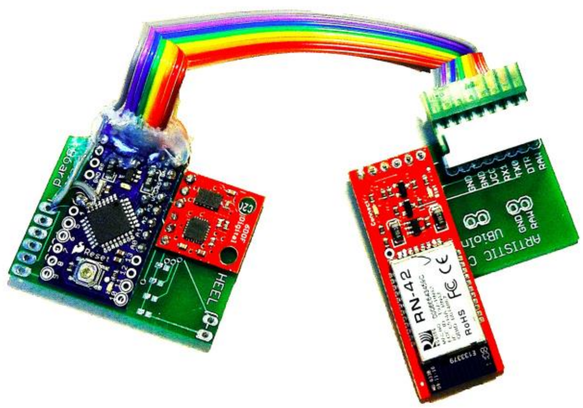

Figure 3.2: PCB boards with Arduino, IMU, and Bluetooth modem mounted to them

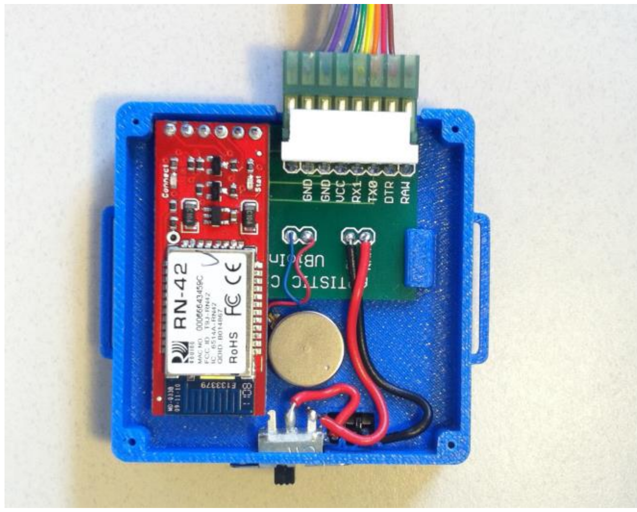

Figure 3.3: Communication box showing Bluetooth modem, PCB, and vibrating motor

Table 3.1 System comparison between ARTISTIC and ARTISTIC 2.0

Specifications:	**ARTISTIC**	**ARTISTIC 2.0**	**% Change**
Weight (g)	103.5	51.3	-50
Volume (mm3 x 103)	150.6	49.6	-67
Sensors (qty)	2	10	+400
Data Rate (Hz)	5	90	+1700
Power Supply (mAh)	565	1500	+165

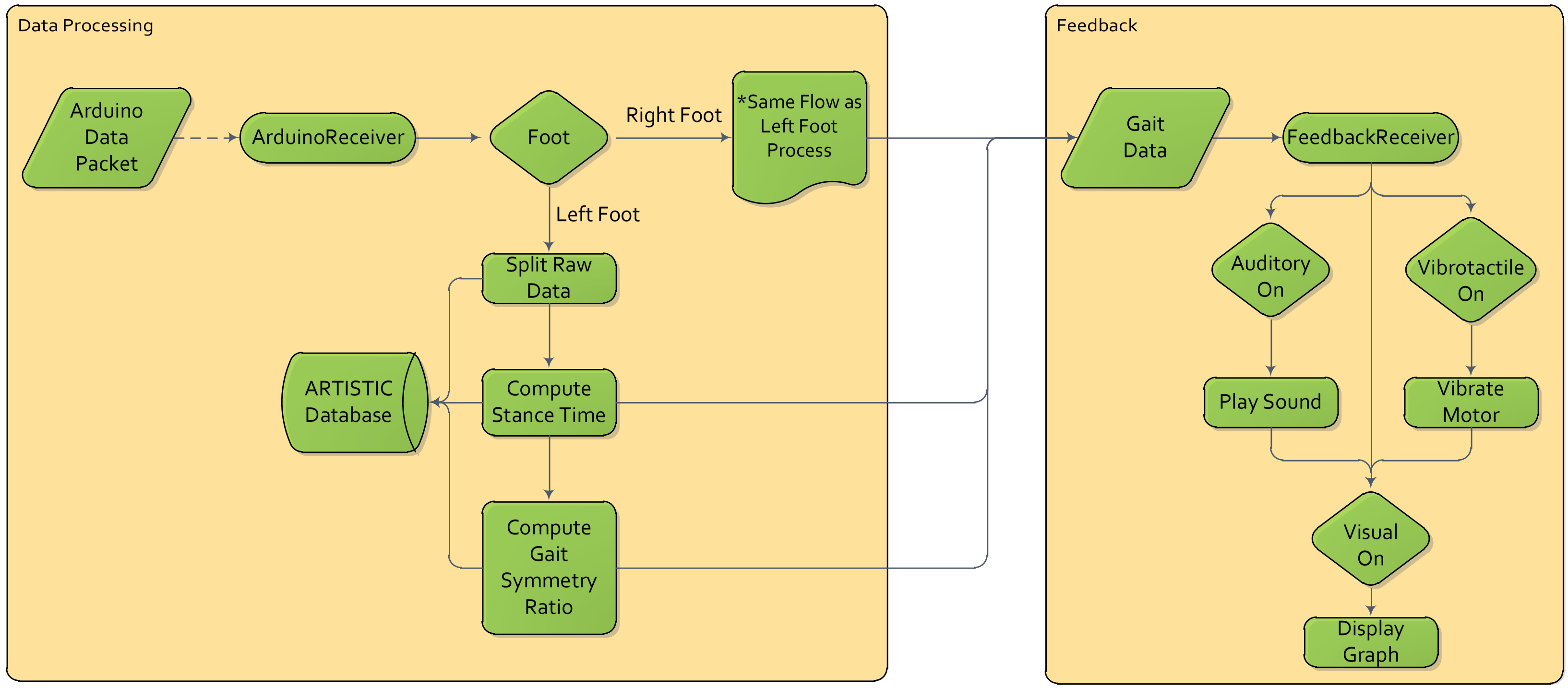

Figure 3.4: Flowchart of data processing and feedback decisions in Android app

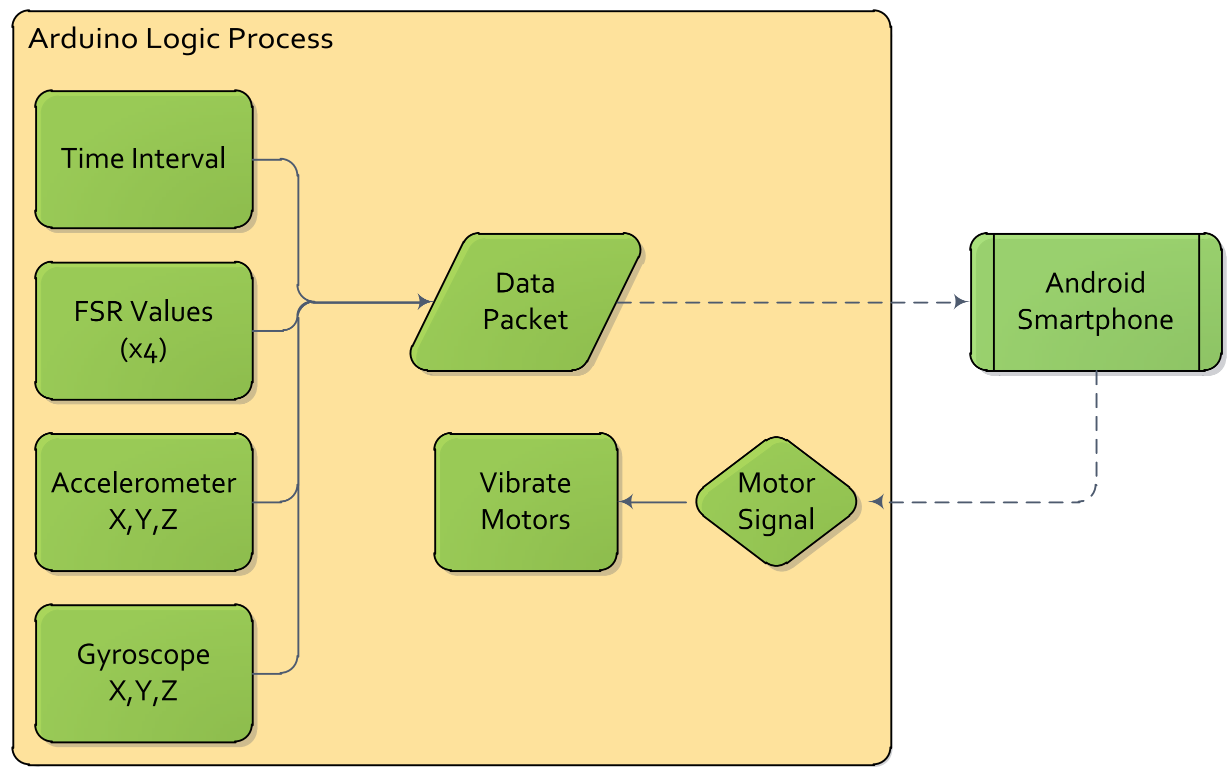

Figure 3.5: Flowchart of sensor polling logic occurring on Arduino microprocessor

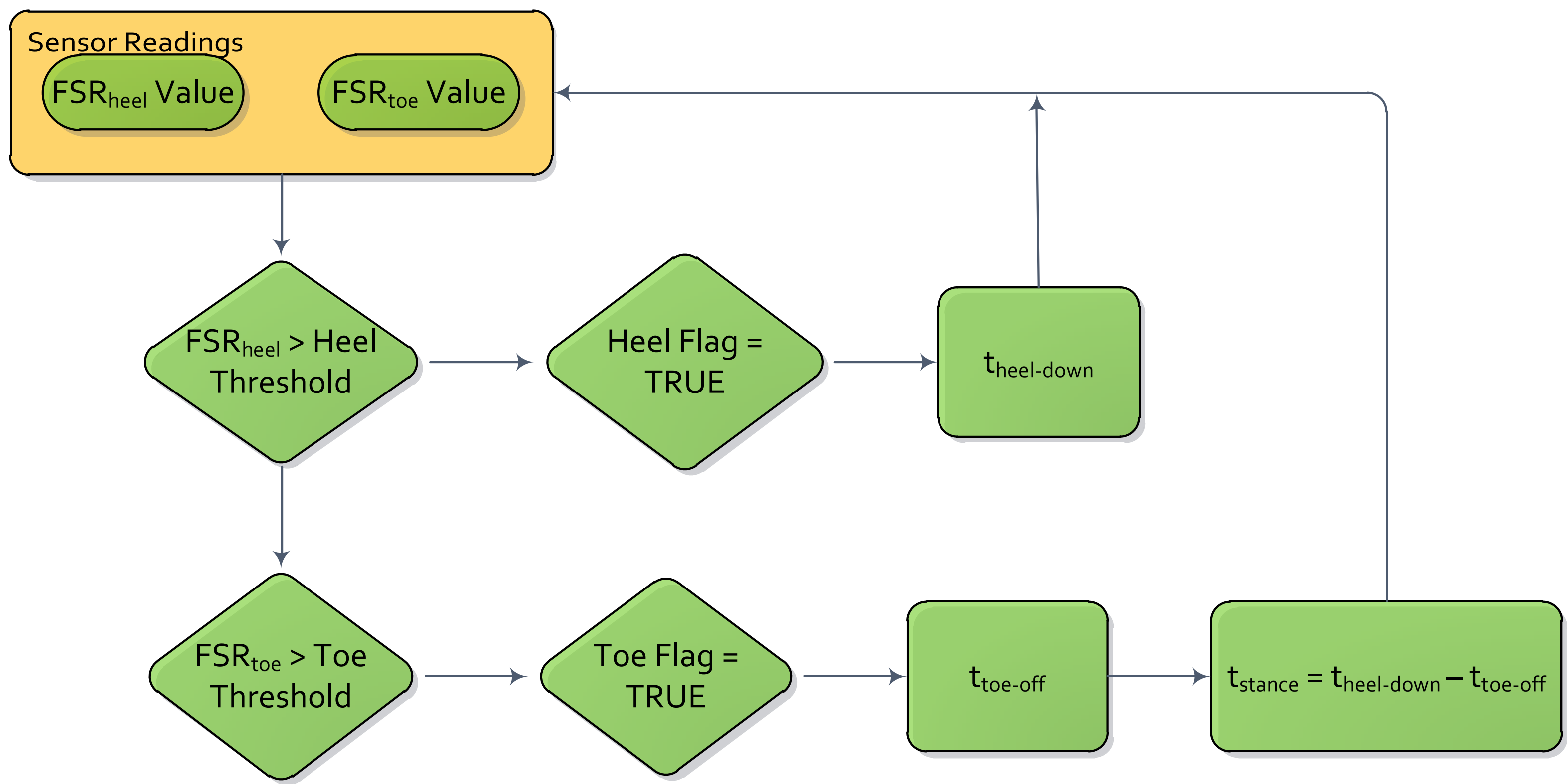

Figure 3.6: Algorithm used by ARTISTIC 2.0 to calculate stance time

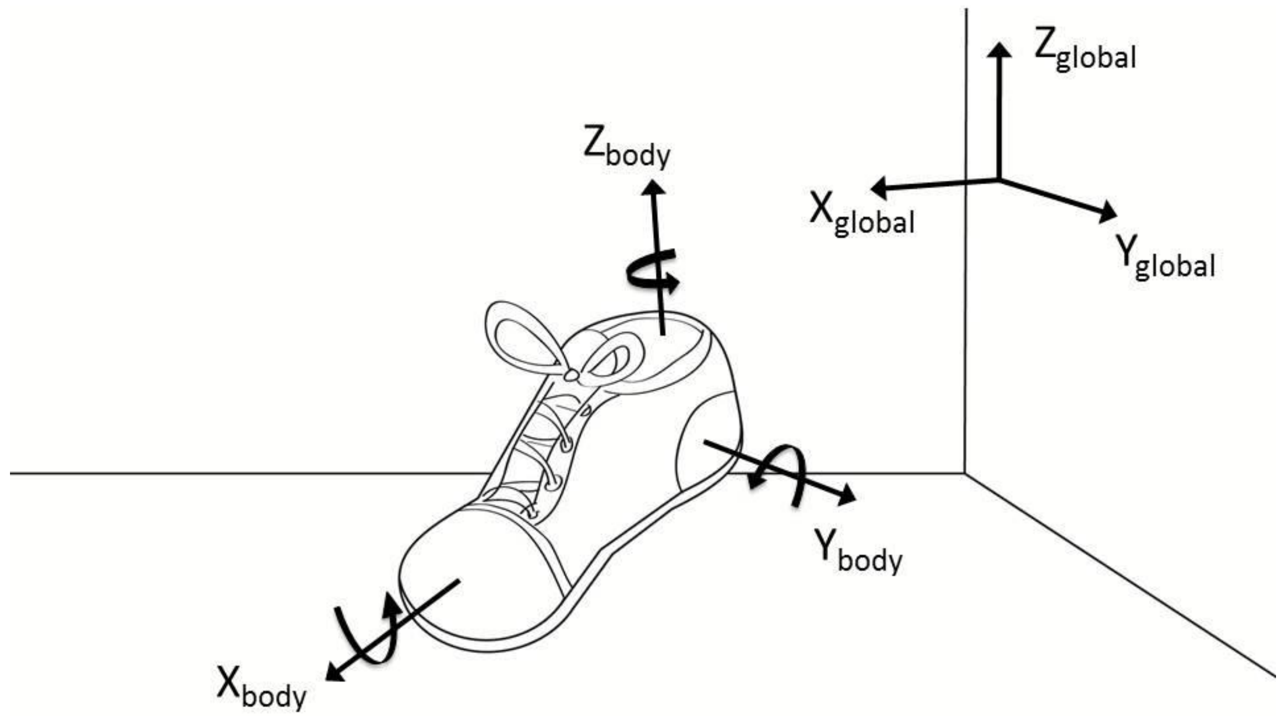

Figure 3.7: Two reference frames used for IMU computation

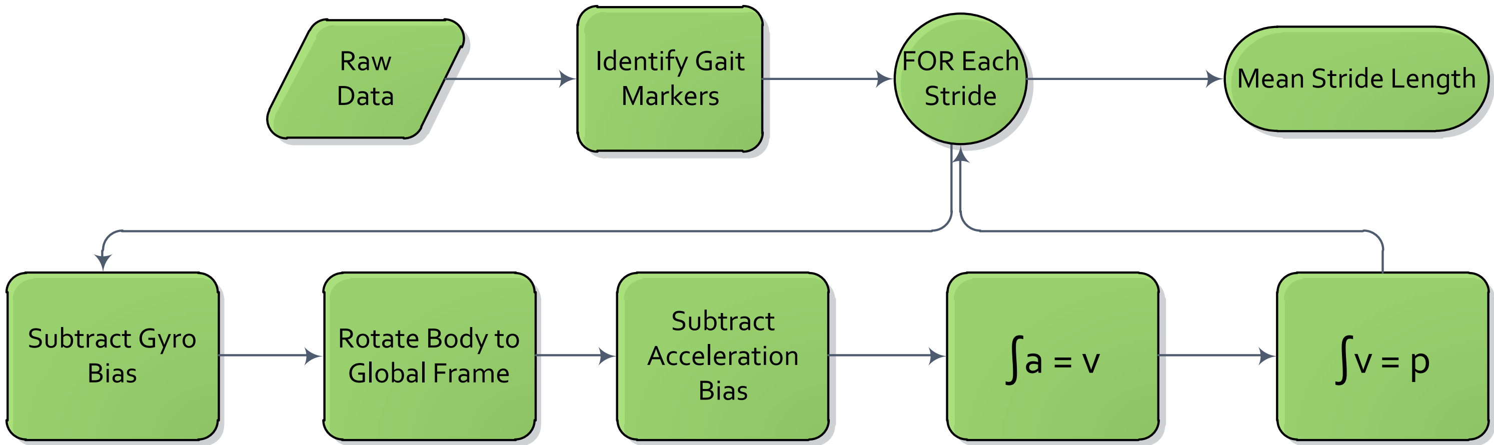

Figure 3.8: Flowchart of IMU data processing

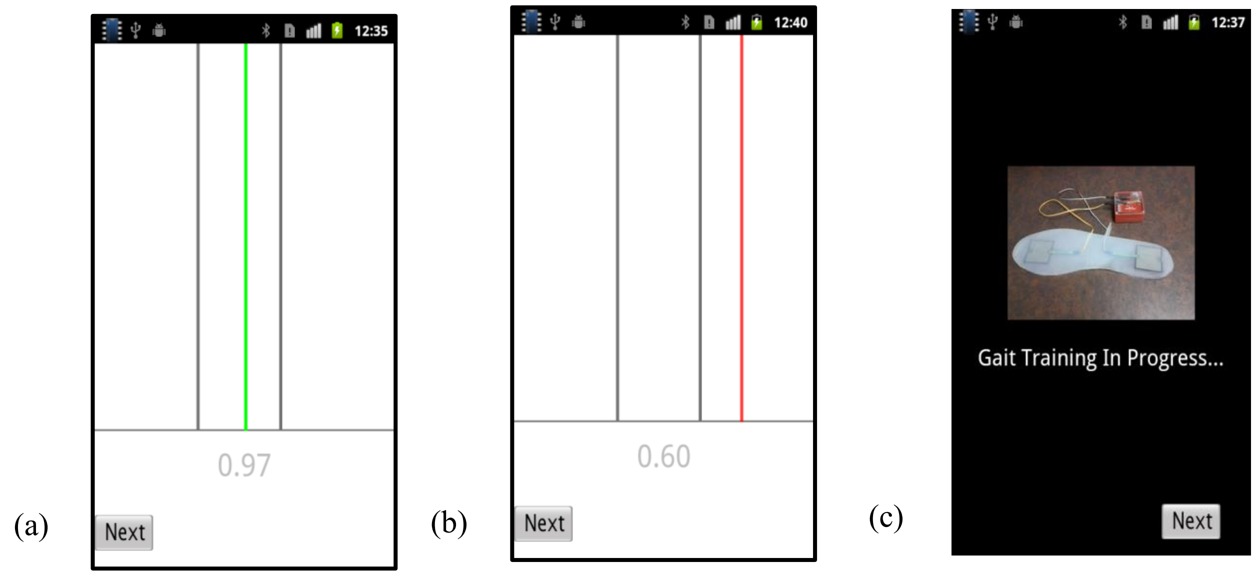

Figure 3.9: Screenshots from ARTISTIC 2.0 app during visual (a and b) and non-visual (c) feedback modes

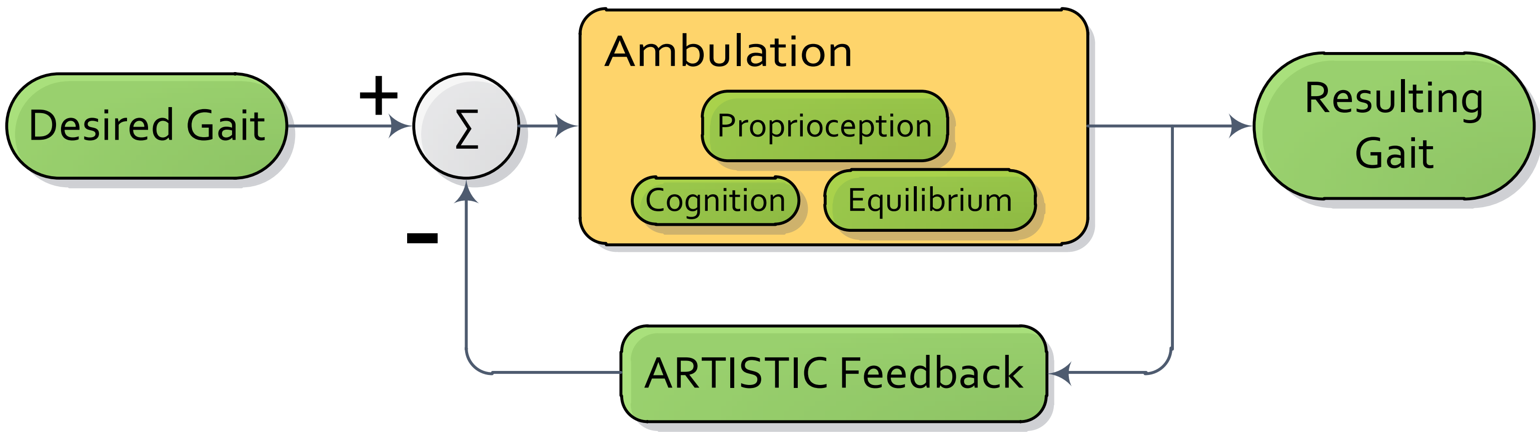

Figure 3.10: Closed-loop feedback as provided by ARTISTIC

Table 2. Stance time comparison between motion capture equipment and ARTISTIC 2.0

Test	Resistor Type	FP Stance Time (s)	FSR Stance Time (s)	Error (%)
1	1k	0.793	0.668	-15.8
2	1k	0.795	0.661	-16.9
3	1k	0.933	0.831	-10.9
4	1k	0.902	0.807	-10.5
			Average	**13.5 ± 3.3**
5	5k	1.006	0.934	-7.2
6	5k	0.919	0.856	-6.9
7	5k	0.860	0.783	-9.0
8	5k	0.839	0.770	-8.2
			Average	**7.8 ± 1.0**

Table 3. Stride length comparison of the motion capture system to the ARTISTIC 2.0

Test	Motion Capture (mm)	ARTISTIC 2.0 (mm)	Error (%)
1	1269.1	1216.4	+4.10
2	1342.9	1234.7	+8.10
3	1235.5	1227.1	+0.7
4	1253.9	1243.6	+0.8
5	1235.9	1367	-10.7
6	1245.4	1399.5	-12.4
7	1234.9	1290.6	-4.5
8	1245.4	1356.9	-8.9
9	1152.4	1205.6	-4.4
10	1206.1	1309.9	-8.6
11	1219.1	1261.1	-3.5
12	1224.4	1135.7	+7.2
		Average	**2.7 ± 6.9**

Table 4. Statistical significance of feedback modes (p-values < 0.05 were considered statistically significant)

Feedback Mode	p-Value	# of Subjects	Power
Gait Symmetry Ratio			
Preferred	**0.014***	6	0.84
Largest Non-Preferred Change	**0.021***	6	0.75
Baseline 2	0.099	5	0.30
Stride Length			
Preferred	**0.019***	6	0.78
Largest Non-Preferred Change	**0.034***	6	0.64
Baseline 2	0.080	5	0.43

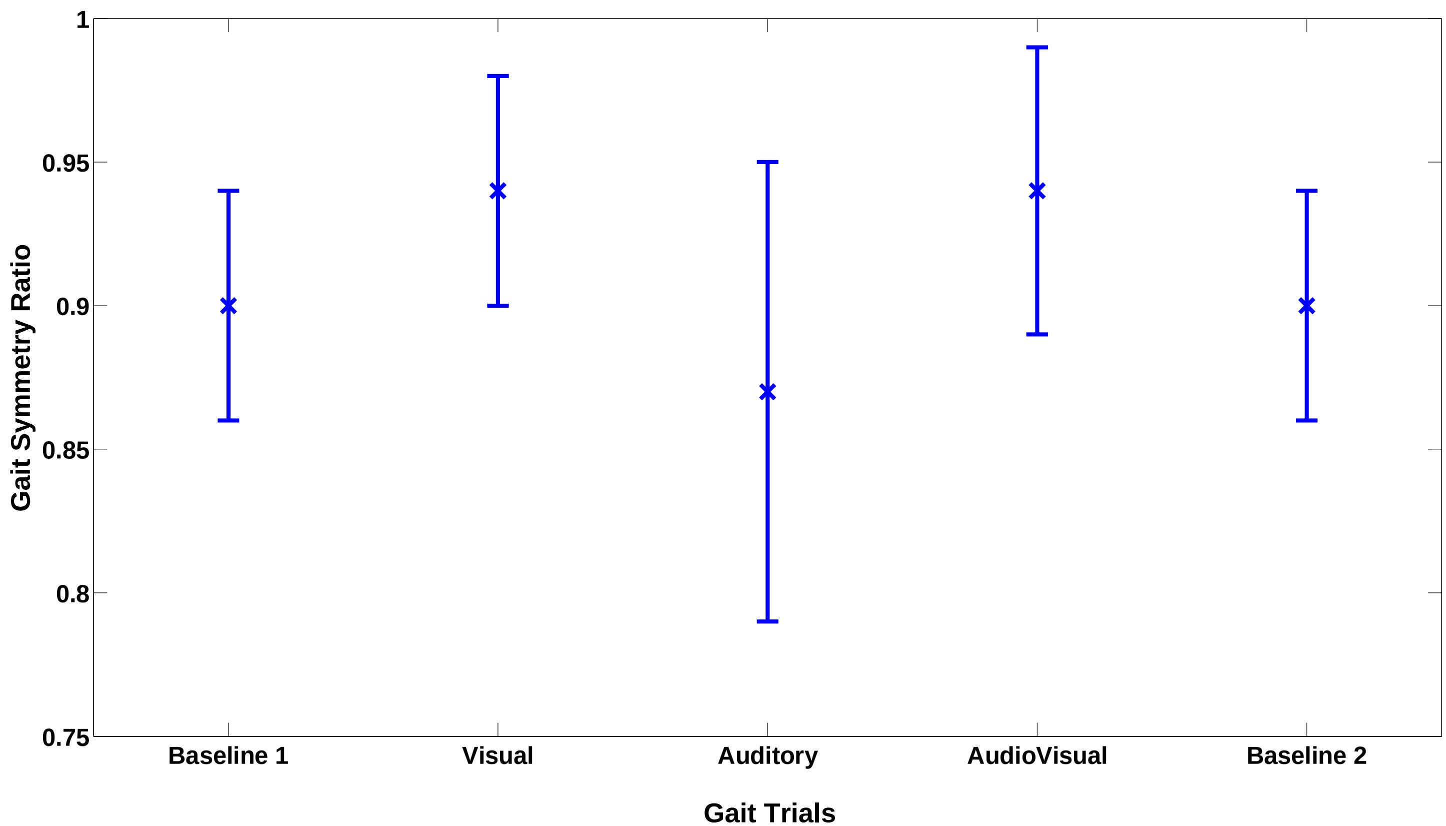

Figure 3.11: Gait symmetry ratio of subject 9 over five trials

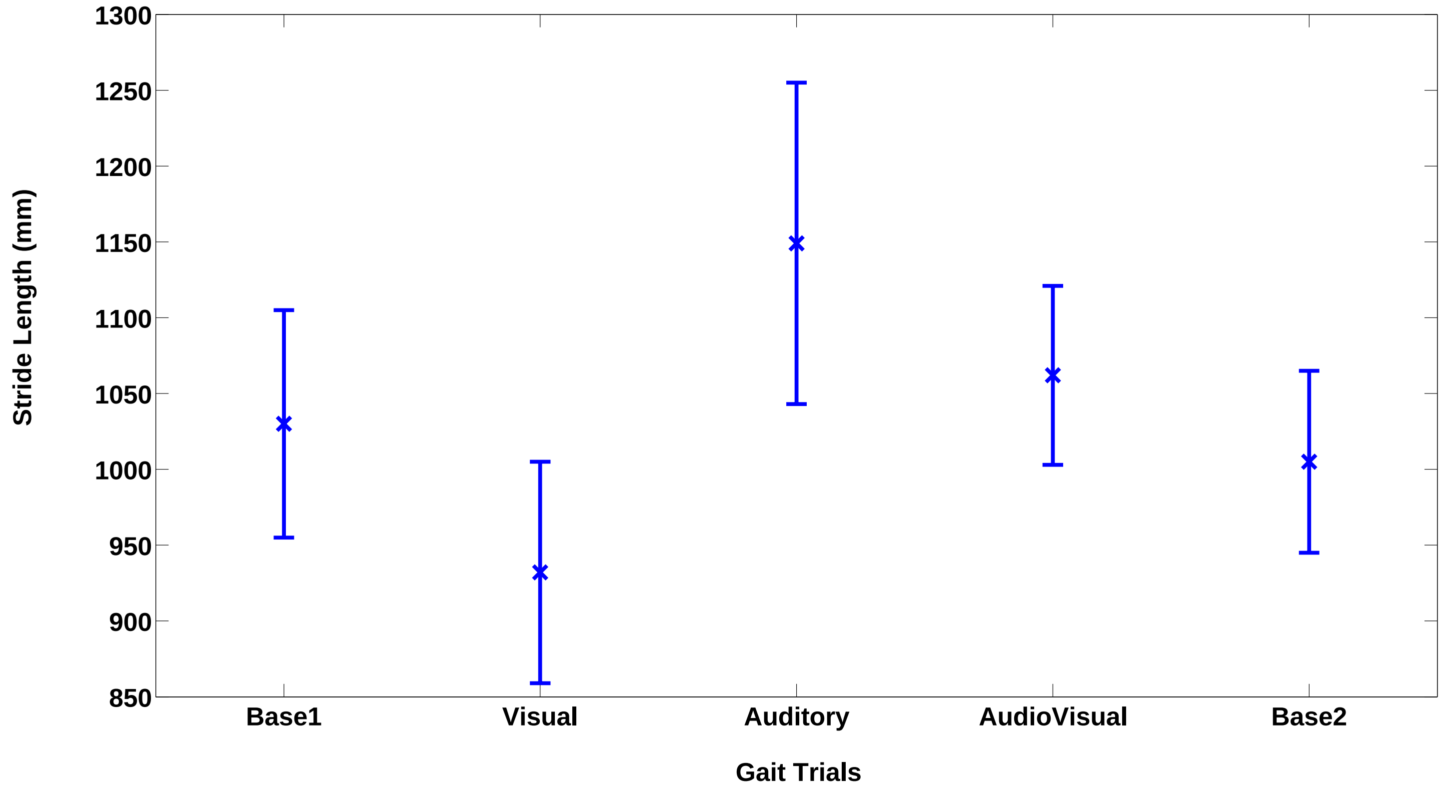

Figure 3.12: Average stride length of subject 9 over five trials

CHAPTER 4

CONCLUSIONS AND FUTURE WORK

This work documents the improvements made to a novel feedback system for gait rehabilitation. Previous work with the ARTISTIC demonstrated that the design interfaces cleanly with an Android smartphone to provide effective feedback for gait retraining [1]. Testing with control subjects showed that the system has the potential to alter gait [2]. However, test subjects overwhelmingly selected the visual feedback mode as a preferred feedback mode due to simplicity of the auditory and vibrotactile feedback cues.

4.1 Conclusions

The contributions of this thesis include revisions made to the auditory and vibrotactile feedback modes. The original auditory feedback mode provided a negative feedback prompt when gait asymmetry exceeded a selected threshold. The improved auditory feedback mode used on the ARTISTIC 2.0 device plays five distinct tones from the diatonic scale of C major during the final 300 milliseconds (ms) of a targeted stance time. Targeted stance times are based on a continuously updating average of previous stance times. This makes the auditory feedback mode a true closed-loop feedback just like the visual feedback mode developed for the previous ARTISTIC design.

Similarly, the original vibrotactile feedback was provided through activating the vibrating motor in the Android smartphone when gait asymmetry exceeded a selected threshold. The improved vibrotactile feedback mode of the ARTISTIC 2.0 device activates a motor inside the insole or communications box, as selected by the user, during the last 300 ms of a targeted stance time.

Significant design changes to the insole included embedding the Arduino microprocessor, an inertial measurement unit (IMU), and a vibrating motor inside the insole. This eliminated most electronics in the communications box, which reduced the weight and size of the boxes from 103.5g and 150,585 mm^3 to only 51.3g and 49,572 mm^3. Additionally, power is now supplied to the ARTISTIC 2.0 device from a 3.7 volt rechargeable battery instead of the 9 volt battery used in the previous design. The change in power sources will reduce power dissipation through the Arudino's builtin voltage regulator from 0.360 Watts to 0.036 Watts. It also increases the lifespan of the ARTISTIC 2.0 a theoretical 16.7 hours of non-stop use.

This work was a positive move towards a mobile gait rehabilitation device capable of tracking multiple gait parameters. An IMU embedded inside the insole is key to monitoring additional gait parameters. Data are now transferred from the insole sensors to the Android smartphone as raw values that are processed in the ARTISTIC 2.0 application. As such, a full database of sensor values can be stored and analyzed during post processing while real-time gait parameter values are used to provide feedback to the user. A matrix of force sensitive resistors (FSR) oriented in the toe and heel of each insole are run through different voltage divider circuits to allow for differentiation between foot switch capabilities and pressure reading capabilities.

A small human subjects study demonstrated that the ARTISTIC 2.0 is capable of altering gait symmetry in as few as 40 steps. The implication is that, provided more time and exposure to the device, persons with abnormal gait symmetries will be able to correct their gait towards a healthier symmetry by using the ARTISTIC 2.0 feedback modes. In addition, the human subjects study demonstrated that there is no single feedback mode that is preferred by all persons. Selection of a preferred feedback mode occurs on an individual basis.

Considering all the improvements that have been made to the ARTISTIC 2.0 device, it is interesting to note that the system still costs less than $400 to manufacture. Since ARTSITIC 2.0 is cost efficient and simple to use, the ARTISTIC 2.0 can reasonably become an at-home gait rehabilitation device.

4.2 Future Work

This work has taken big steps in the positive direction towards creating a diverse mobile gait rehabilitative device. Yet, further improvements to the system will make it even more powerful in gait retraining.

The wireless transfer of raw sensor data from the microprocessor to the smartphone was conducted using Bluetooth modems. These modems are rated to be capable of transmitting up to megabytes per second worth of data. The design presented in this work could stream 11 channels of data at a maximum 90 Hz. This represents an overall transmission rate of between 1,980 – 4,680 ASCII bytes per second. If data were transmitted faster than this the Bluetooth modem in the communications box would reset itself. Investigation should be made into causes of this self-reset error.

Auditory and vibrotactile feedback modes did not deliver feedback signals at the precise instant in time assigned to that signal. There was sometimes a lag between feedback signals. It is believed that any lags are due to using a separate thread in the smartphone application with a queuing method to play tones or vibrate a motor. These feedback modes could be further improved by delivering feedback signals directly through independent processing threads on the smartphone. Any use of queuing should be eliminated.

A SQLite database was designed for this work but never implemented because of the complexities of interprocess communication and threading on the Android smartphone. During attempts to utilize the database, the Android application consistently crashed because the user interface process was being delayed too much. Persisting all data into a SQLite database on the smartphone will open up possibilities of presenting information at various times during gait retraining. For example, it could be used to display graphs of gait parameters such as asymmetry ratio during or after a training session.

The ARTISTIC device currently consists of two sections for each foot: an insole and a communications box. Further iterations of the ARTISTIC design should focus on moving the battery and Bluetooth modem into the insole. It has been suggested that a custom arch could be built for each insole. The arch could house all electronic components including microprocessor, IMU, Bluetooth modem, and battery.

4.3 Summary

The ARTISTIC 2.0 device is a rehabilitative device that provides real-time feedback methods to assist in correcting gait. The feedback modes provided by the device are visual, auditory, and vibrotactile. The device is also capable of providing a combination of feedback modes simultaneously to enhance the user experience. Improvements were made to a previous version of the device through an extensive redesign of the device hardware, software, and feedback modes. The ARTISTIC 2.0 is simple and inexpensive. As such, the device is a plausible option for at-home rehabilitation.

4.4 References

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